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Analysis of a Quasi Resonant Switch Mode Power Supply for Low Voltage Applications

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***Abstract*—QRC provides efficient and regulated switch mode power supplies for robotic and satellite applications. This paper addresses the enhanced controller techniques for high frequency isolation based push-pull Quasi Resonant Converter. This technique is similar to the conventional PI controller technique but varies only the enhancement constants to improve the time domain response of the converter. The proposed converter is designed for low output voltage and power rating, characteristically 5V and 5 W, with the comprehension of current design trends towards enhanced performance. At the primary stage, to validate the design of the converter, simulation is performed in PSIM for ±50% load variations. A prototype model of this converter is developed. The results obtained from the experimental set-up are presented and analysed in detail. The results reveal the superiority of the proposed method.**

***Index Terms*— Power supply, Push-pull Converter, Zero Voltage Switching, Enhanced PID controller, Quasi Resonant Converter (QRC)**

I. Introduction

Low voltage applications like switch mode power supplies for Robots and aerospace applications insist in smaller size power supplies for powering the servo motor used in robots and for powering the transmitter and receiver of satellites. Hence for these applications Push-Pull converter is chosen and analysed in detail in this paper. This converter has the following advantages - it is an efficient converter in the low power range, it has an inbuilt isolation transformer, good transformer utilization factor and double the power output than its same rated forward converter counterpart. To add on to these advantages ZVS technique is incorporated across the switches to reduce the switching losses and high switching frequency is selected for reducing the size and weight of the converter [6] – [15].

Selection of higher switching frequency tend to decrease the component size and on its counter shoots the switching losses high at both turn on and turn-off of the switch. This leads to a considerable power loss, high electromagnetic pollution and the oscillations caused by converter parasitic elements. The above mentioned disadvantages results in high current and voltage stresses, which are almost unpredictable, depending on circuit layout. Liu and Lee reported new topologies to decrease the switching losses at high frequency operation [1]. Several new topologies arose as reported in [2] – [5] and are widely used in industrial application for their advantages like smaller size, limited radio-frequency disturbances and absence of switch current and voltage spikes.

The converter presented here is suitable for robotic applications as a switched mode power supply up to several hundreds of Watts. It employs a ZVS-half wave push-pull structure, which allows full exploitation of the transformer core and high power density [7], [11] – [14]. The control techniques normally used to control switching power supplies is Pulse-width Modulation (PWM). The linear controllers like P, PI, PID and enhanced controllers like EPI and EPID are used to produce PWM signal to actuate the switch [10], [14]. The authors have already reported the topology with PI technique [14]. This paper is a extended work of the paper with analysis of the enhanced controllers like EPID and EPI. The simulation and experimental results for a closed loop analog controller based 5W, 50 kHz single-output ZVS half wave push-pull converter industrial prototype for robotic and satellite applications are discussed in this paper.

II. Push-pull ZVS Quasi Resonant Converter

The quasi resonant waveforms of the converter in Fig.1 are shown in Fig.2. Any switching action in the converter changes the circuit configuration or modes. This converter has six such operating modes as explained in [7]. The specification and designed values of the converter are as tabulated in table I. The open loop simulation, closed loop simualtion and hardware implementations are carried out with these designed values.

III. Open Loop Simulation

The open loop simulation of the converter shown in Fig.1 is simulated in PSIM. The output voltage (Vo) and current (Io) obtained are presented in Fig.3. The resonant waveforms of the primary capacitors and inductors are shown in Fig.4. The figure clearly depicts that the primary switches are turned ON at zero crossing of the resonant capacitor voltage (i.e) voltage across the switches. Hence the switching losses are drastically reduced. It is also observed that the resonant waveforms (the voltage across the resonant capacitors and the current through the resonant inductor) are not distorted even under load variations. The resonant waveforms for ±50% of load variations are shown in Fig.5 to Fig.8. From Fig.5, Fig.6 and Fig.7, Fig.8, it is pragmatic that the peak capacitor voltages and inductor currents are in the range of 45V to 50V

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and 0.8A to 0.9A for ±50% of load variations and the resonant curve shapes are also prevailed throughout the load changes applied. Hence this converter can be efficiently used as a switched mode power supply for load varying environments as the resonance and hence the switching losses are not disturbed during load variations.

TABLE I. SPECIFICATION AND DESIGN

Parameters	Specification / designed values
Input voltage	15± 5V
Output voltage	5 V
Output Current	1 A
Resonant inductor	160µH
Resonant capacitor	0.047µF
Filter inductor	4.7µH
Filter capacitor	220µF

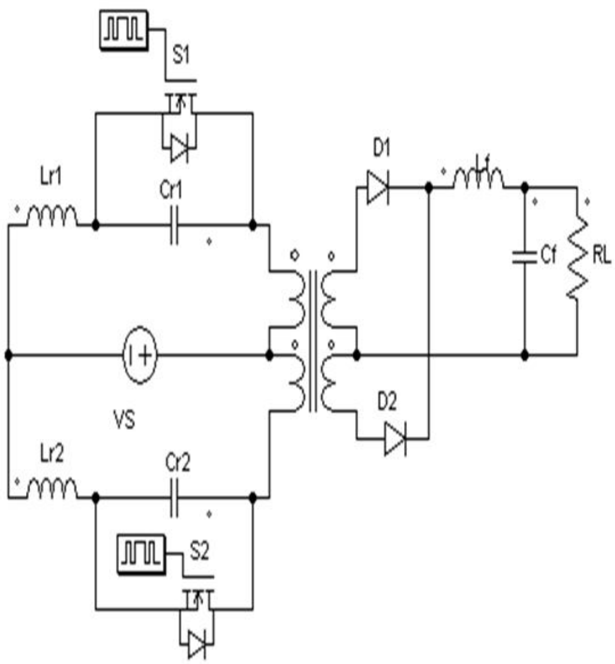

Figure 1. Circuit diagram of push- pull ZVS-QRC converter.

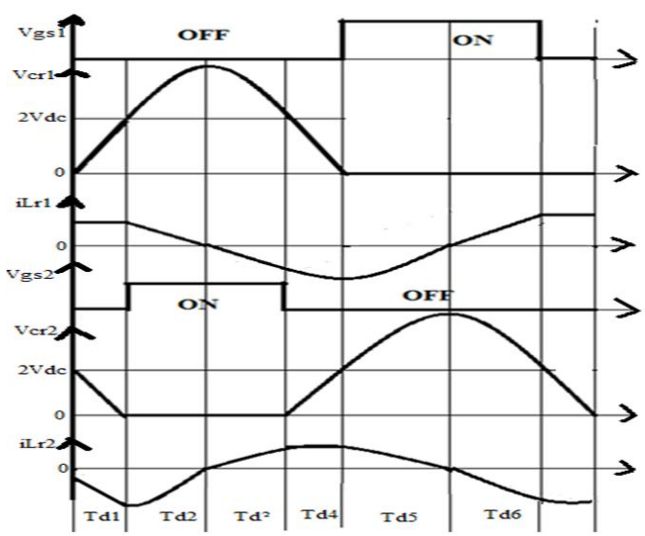

Figure 2. Idealised resonant waveforms of SISO ZVS push-pull converter.

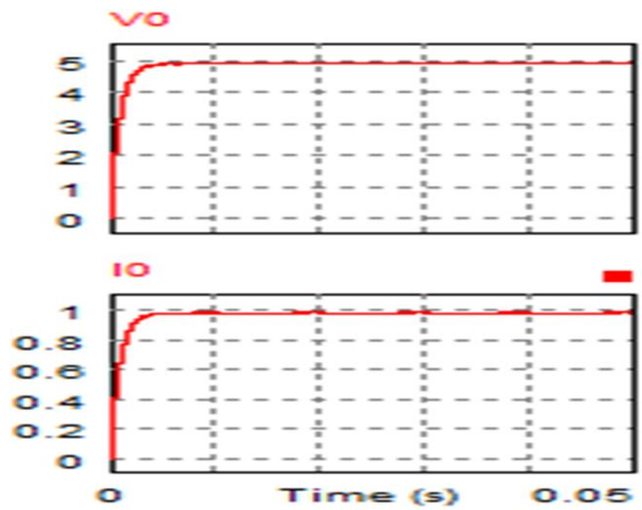

Figure 3. Converter output voltage and current waveforms.

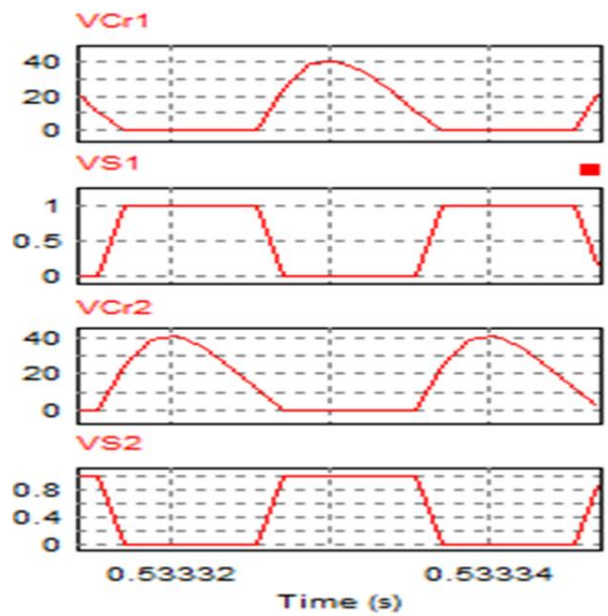

Figure 4. Resonant waveforms of SISO ZVS push-pull converter.

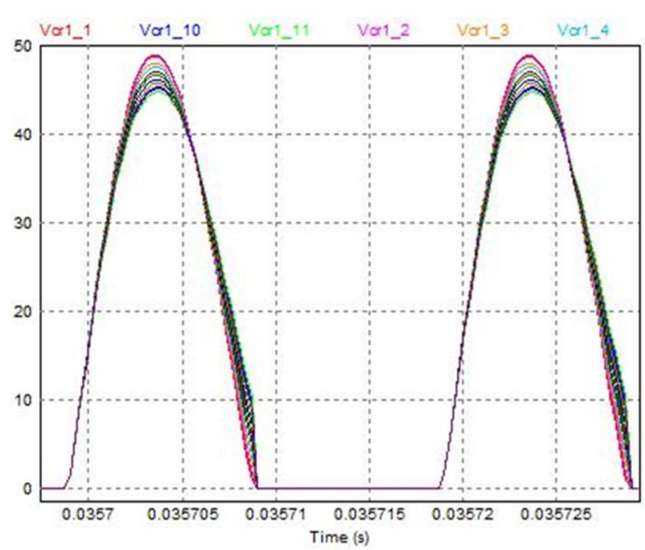

Figure 5. Resonant Capacitor1 waveforms for ±50% load changes.

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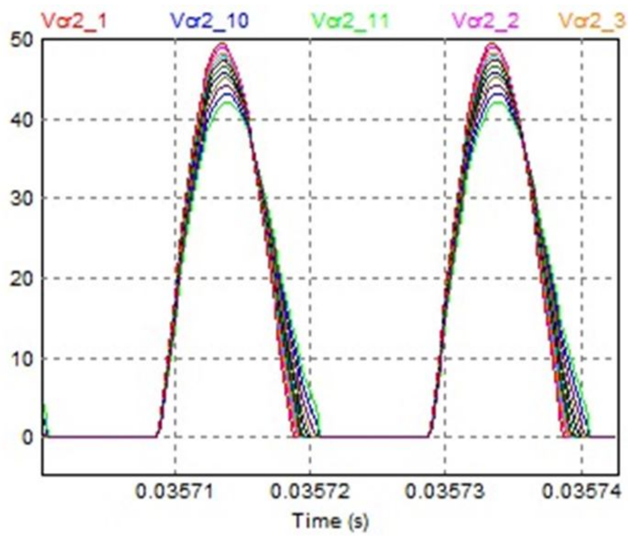

Figure 6. Resonant Capacitor2 waveforms for ±50% load changes.

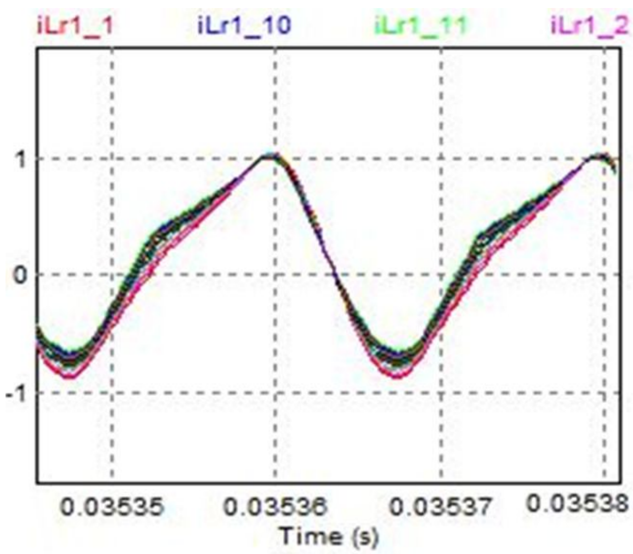

Figure 7. Resonant Inductor1 waveforms for ±50% load changes.

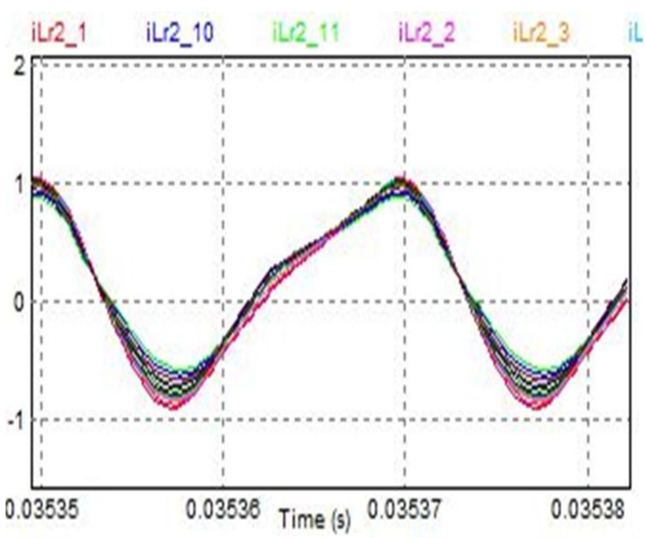

Figure 8. Resonant Inductor2 waveforms for ±50% load changes.

IV. Closed Loop Simulation

Closed loop operation of the converters always provides regulated output voltage under load and supply variations; hence it is preferred than open loop control. Two commonly used control schemes to regulate the output voltage of dc-dc converters are voltage-mode control and current-mode control. Both control schemes have been widely used in low-voltage low-power switch-mode dc-dc converters integrated circuit design in industry. The feedback loop automatically maintains a precise output voltage regardless of variation in input voltage and load conditions. The voltage feedback arrangement is known as voltage-mode control when applied to dc-dc converters. Voltage-mode control (VMC) is widely used because it contains only a single feedback loop from the output voltage, hence, it is easier to design and implement compared to current control mode. Further it responds immediately to the disturbances at the reference input. A closed loop controllers with VMC is designed and implemented in the proposed push-pull DC-DC converter. The controller consists of three units. The first is an error amplifier which gives the actual load variation of a regulated output with reference to the designed output value. The second is a controller which generates a control signal proportional to the error signal given by the error amplifier. The final unit is a PWM generator which generates a series of pulse which triggers the converter switch.

The simulation of the closed loop circuit is carried out in PSIM to confirm the working of the converter in closed loop operation. The closed loop operation was carried out with the following four different controllers

(a) PI Controller
(b)PID Controller
(c)EPID Controller
(d) EPI Controller

The results obtained are presented and analysed in detail in this section.

A. *PI Controller and PID Controller*

The closed loop simulation circuit incorporating the PI controller and the converter are explained in [14]. It is further discussed by the authors that the resonance and output ranges are as designed and that the closed loop simulation of the circuit confirms the perfect functioning of the converter with the PI controller circuit whose controller output is given as in (1).

$$P = K_P(Y_{sp} - Y) + K_P K_I \int (Y_{sp} - Y)dt \qquad (1)$$

where P- controller output, Kp- proportional constant, Ysp- desired set point, Y- measured output voltage, K_I- Integral constant. The integral term of a PI controller varies the output as long as there is a non-zero-error. Therefore, such a controller can eliminate even a small error. An electronic PI controller designed for the proposed converter is as explained in [14].

A PID controller produces output based on the present error. Error is calculated from the measured output voltage and a desired set point. The controller tries to reduce the

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error by processing the error. The PI parameters such as Kp, Ki, Kd used in the equation (2) are varied based on the nature of the system. The controller output is illustrated in the following equation.

$$P = K_p(Y_{sp} - Y) + K_pK_I \int (Y_{sp} - Y)dt + K_pK_D \frac{d(Y_{sp} - Y)}{dt} \quad (2)$$

Where K_D- Derivative constant.

Kp reacts to the present error, the integral part reacts to the cumulative errors and the derivative part reacts to the rate of change of error. The weighted sum of these three actions is used to produce the PWM pulse. Based on the error, controller produces the variable output and this is used to vary the duty cycle of the PWM pulse.

B. EPID Controller

Enhanced PID controller (EPID) produces the output to reduce the peak overshoot and settling time by adjusting the values of constants b and c of (3). The controller output is illustrated in the following equation.

$$P = K_p(bY_{sp} - Y) + K_pK_I \int (Y_{sp} - Y)dt + K_pK_D \frac{d(cY_{sp} - Y)}{dt} \quad (3)$$

where b and c are enhancement constants. They control the error input. The value of b and c are chosen between 0 and 1. Enhanced control algorithm does not affect the PI parameters. By adjusting b and c value, peak overshoot and deviation from error can be reduced [10]. Over all dynamic performance of the controller is improved by adding enhancement constants.

C. EPI Controller

Enhanced PI controller (EPI) works as the EPID with the derivative component removed and its control equation is as given in (4)

$$P = K_p(bY_{sp} - Y) + K_pK_I \int (Y_{sp} - Y)dt \quad (4)$$

The circuits simulated for PID and EPID are as shown in Fig 9. and Fig.10, PI and EPI circuits resemble the same without the derivative D block.

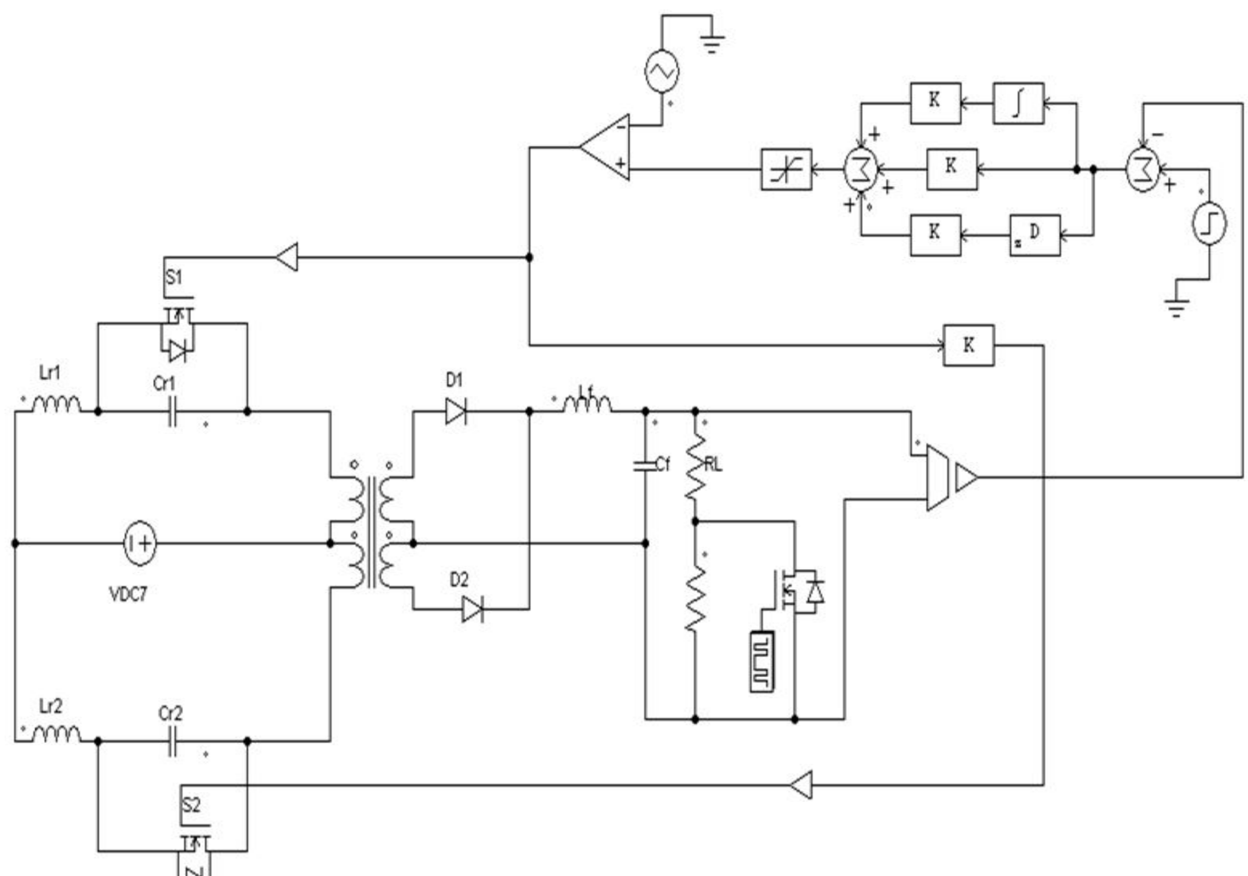

Figure 9. Converter circuit with PID controller.

V. Analysis

The controllers stated above are simulated with the converter and the output voltage was observed to be regulated for 2Ω change (both increase and decrease). The observed waveforms are presented in the Fig. 11 to Fig.14. The regulated waveform for load increase from 5 Ω to 6 Ω and 7Ω respectively are shown in the Fig.11 and Fig.12, the load current change was observed to be 0.8 A and 0.7A respectively from the steady state value of 1A. Similarly for 1 Ω and 2 Ω decrease in the load corresponding increases in current from 1A to 1.35A and 1.6A respectively and is observed in the Fig.13 and Fig.14. Both cases of increase and decrease in load is being noted as a small disturbance at exactly 0.5sec, were load change has been applied. The closed loop operation results in a stable, less oscillatory, less overshoot,

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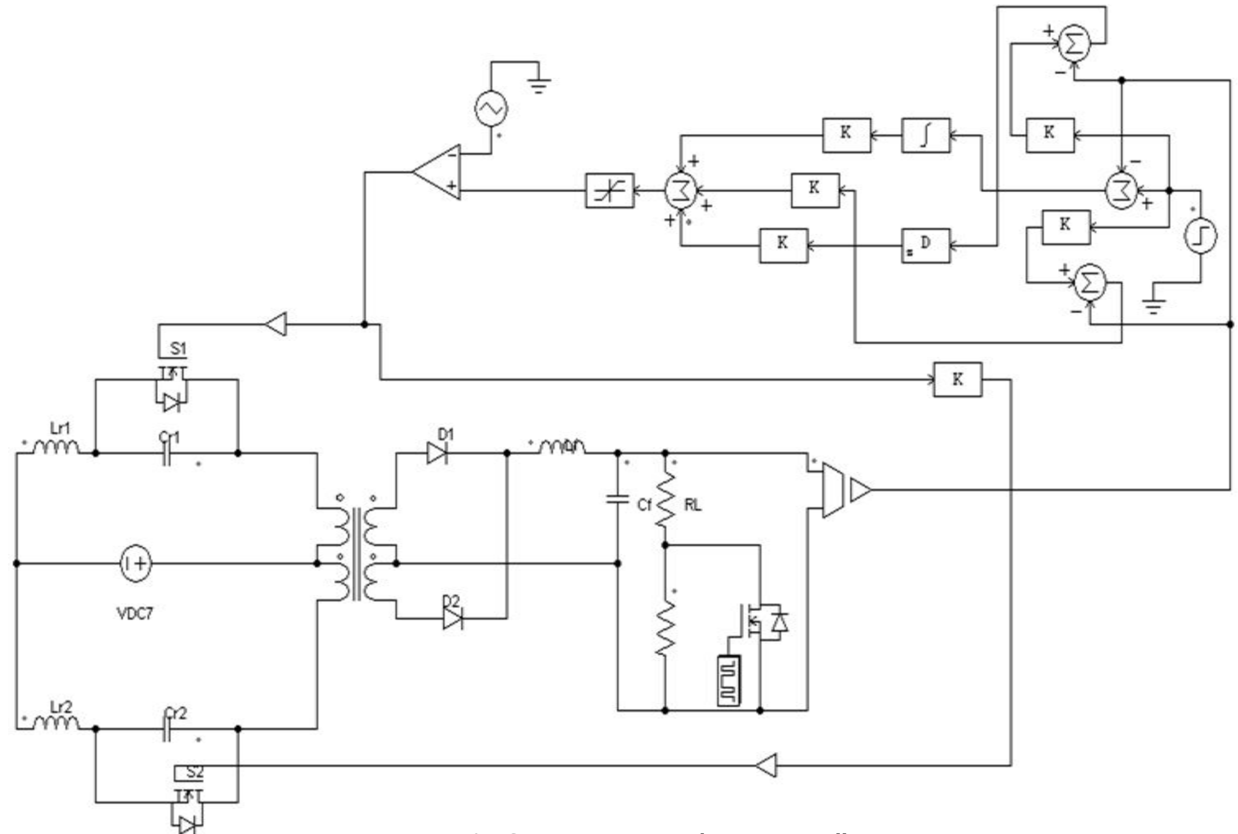

Figure 10. Converter circuit with EPID controller.

less settling time response as observed from the Fig. 11 to Fig.14. The time domain analysis of these waveforms was also carried out and its corresponding values are tabulated in Table II. From the data tabulated in the table II, the response of EPID controller is quicker (i.e.) lesser peak time, settling time, and less overshoot also when compared with other converters. The same is observed for load change condition also. Hence EPID Controller can be a best option for the switched mode power supplies with stringent regulation. The effect of reducing the maximum peak overshoot reduces the load current and inductor current and maintains them to be within the allowable limits. The enhancement coefficients introduced reduces the error change and makes the system to settle faster with a lesser settling time and stringent voltage regulation. Hence EPID improves the dynamic performances of the system.

The efficiency of the converter is obtained for load varying from 2 Ω to 7 Ωand for a input supply voltage change from 14V to 16V as shown in fig.15. It is observed from the graph that the efficiency is 85.53% at 5W output power, 15V input supply. Additional the efficiency are 84.54%, 86.16% respectively for 5W output power under 14V and 16V input supply respectively. From the graph it’s clear that the converter operates effectively in the output power range of 4W to 6W.

VI. Hardware Implementation

The closed loop push-pull ZVS-QRC with PI controller operating in buck mode is implemented with the designed parameters. The gating pulses derived from the closed loop controller circuit are as shown in Fig.16. The resonant capacitor voltages V_{crl} and V_{cr2} are shown in Fig.17 and 18 with the corresponding gating pulses. The output voltage (V_O) and current (I_O) of the converter obtained are as shown in Fig.19 and Fig.20 and the obtained values are same as that of the specification. It is observed from Fig.17 and Fig.18 that the resonant waveforms are analogous to the theoretical waveform shown in Fig. 2 and the simulated waveform as shown in Fig 4. The results shown in Fig. 16 to Fig. 20 are detailed in Table IV and the components used for implementation are tabulated in Table III.

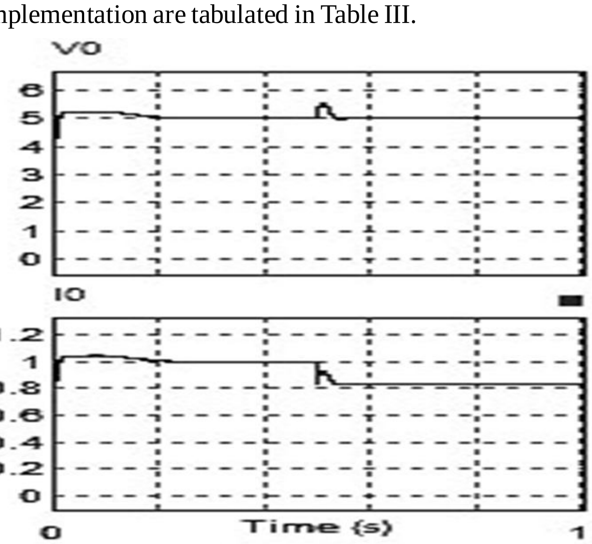

Figure 11 Output Voltage and current for 1 Ω increase in the load.

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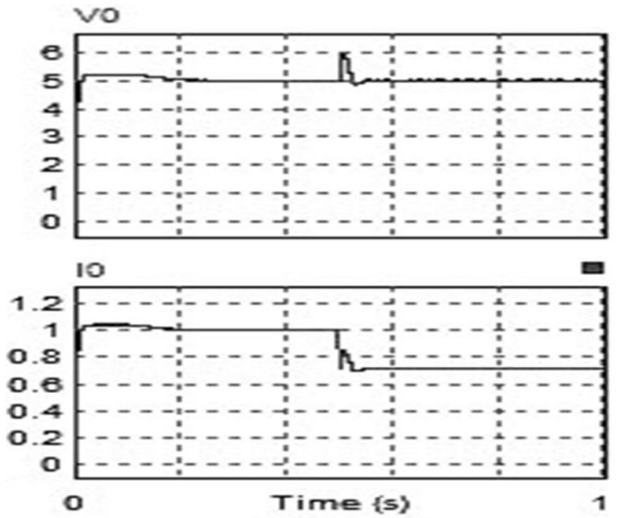

Figure 12. Output Voltage and current for 2 Ω increase in the load.

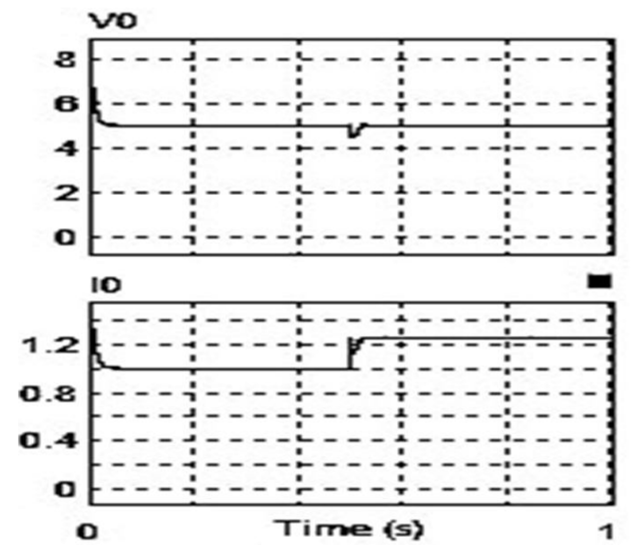

Figure 13. Output Voltage and current for 1 Ω decrease in the load.

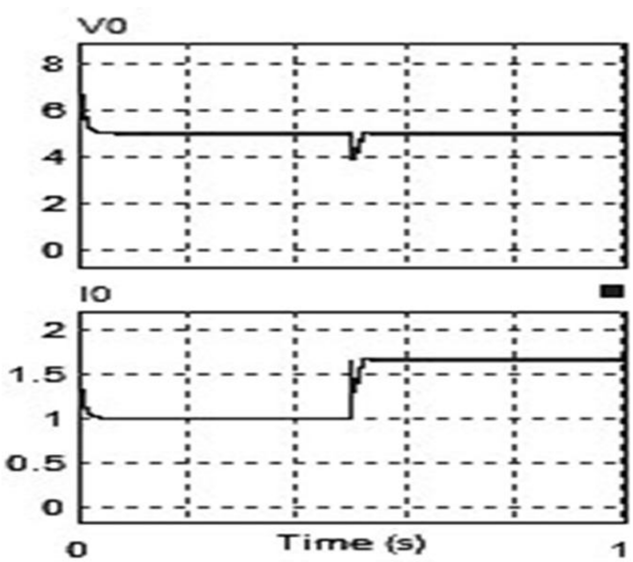

Figure 14. Output Voltage and current for 2 Ω decrease in the load.

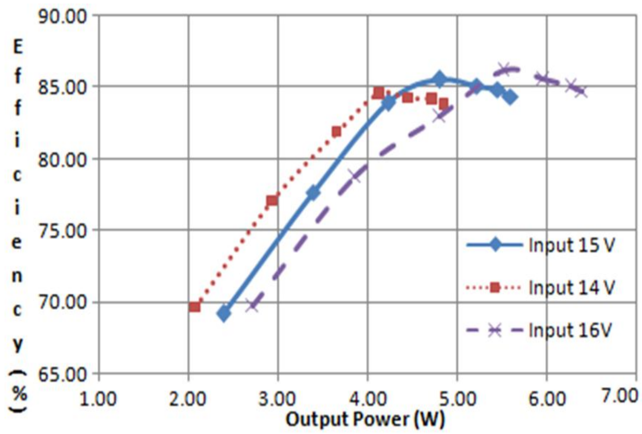

Figure 15. Efficiency curves for load and supply changes.

TABLE II. TIME DOMAIN ANALYSIS

Parameters	Controllers			
	PID	EPID	EPI	PI
Before Load Change				
Peak time (tp in msec)	0.370	0.326	0.352	0.353
Peak Overshoot (V)	5.216	5.213	5.213	5.215
Settling time (ts in sec)	0.223	0.190	0.190	0.190
After load change				
Peak time (tp in msec)	5.932	5.992	5.988	5.978
Peak Overshoot (V)	0.0492	0.0366	0.039	0.0366
Settling time (ts in sec)	7.96	7.9276	8.17	8.37

TALBLE III. HARDWARE COMPONENTS USED

Converter element	Device used	Device number
Active switches	Power MOSFETs	IRF540
Freewheeling diodes	Fast recovery schottky diodes	BA159
PI controller	OPAM	OP07

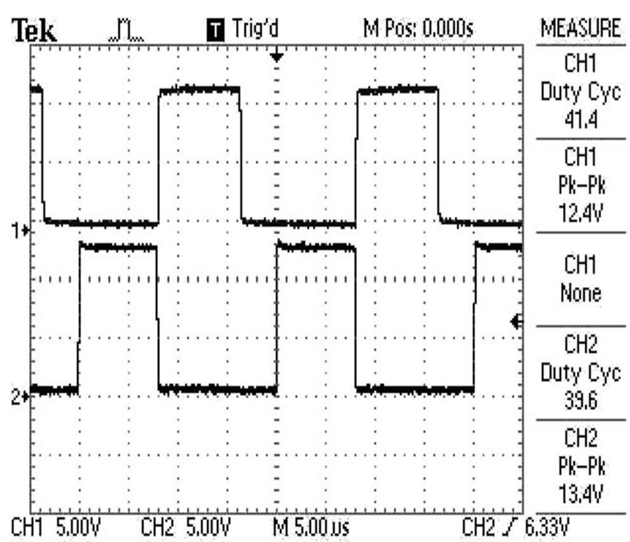

Figure 16. Switching pulses for the active switches.

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TABLE IV. HARDWARE OUTPUTS OBTAINED

Specification	Hardware Results
Switching pulse 1 and 2 amplitude	˜ 13V
Pulse width of pulse 1	39.6%
Pulse width of pulse 2	41.4%
Frequency of gating pulse 1 &2	50kHz
Resonant capacitor voltage(Vcr1)	48V
Resonant capacitor voltage(Vcr2)	37.8V
Output voltage (V_0)	5V
Output Current (I_0)	1A

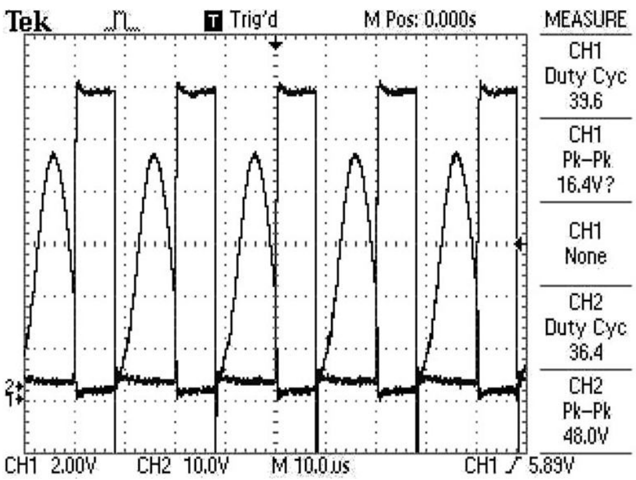

Figure 17. Resonant capacitor1 voltage and switching pulse1 waveform.

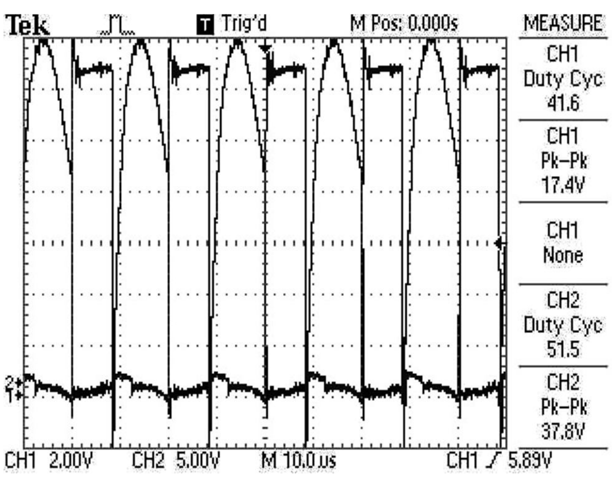

Figure 18. Resonant capacitor2 voltage and switching pulse2. waveform.

VII. CONCLUSIONS

Analysis of simulation and hardware results of the converter reveals the following conclusions. Hard switching increases the switching losses at high frequencies and hence the soft switching technique implemented reduces the switching loss and voltage stress in the active switches. The regulation techniques used for regulating the output voltages are

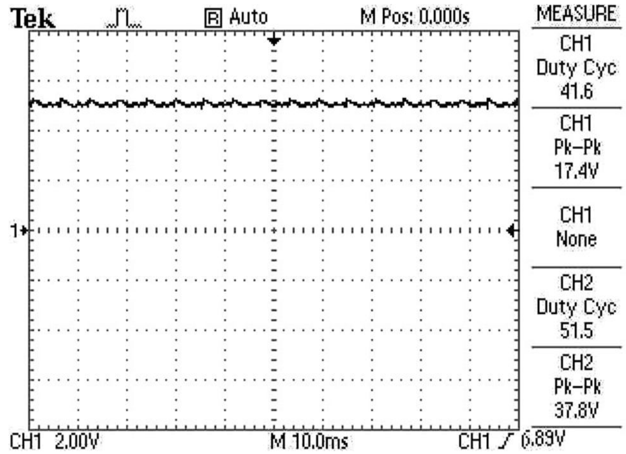

Figure 19. Output voltage waveform.

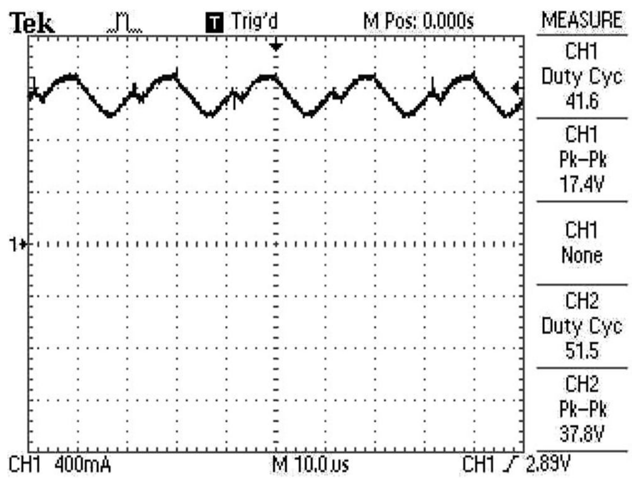

Figure 20. Output current waveform.

PI, PID, EPI and EPID. The time domain parameters obtained from the converter fed from these controllers clearly prove that enhanced PID technique has more advantages like lesser peak time, settling time, and overshoot than the other techniques. The same is observed for load change condition also. Hence EPID Controller can be a best option for the switched mode power supplies with stringent regulation. Reduced maximum peak overshoot helps in maintaining the load current and inductor current within the allowable limits. In a nutshell EPID improves the dynamic performances of the system. The efficiency of the converter designed is 85.5% and could be further increased by designing the transformer with lesser leakage inductance and by reducing the parasitic capacitance between the connecting wires and in layout.

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